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SHAKE TEST OF ROTOR TEST APPARATUS WITH BALANCE DAMPERS IN THE 40- BY 80-FOOT WIND TUNNEL

Wayne Johnson and James G. Biggers

U.S. Army Air Mobility R&D Laboratory
and
Ames Research Center
Moffett Field, Calif. 94035

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A shake test was conducted to determine the dynamic characteristics of a Rotor Test Apparatus on two strut systems with balance dampers in the Ames 40- by 80-Ft Wind Tunnel. The rotor-off hub transfer function (acceleration per unit force as a function of frequency) was measured in the longitudinal and lateral directions, using a combination of broadband and discrete frequency excitation techniques. The dynamic data are summarized for the configurations tested, giving the following properties for each mode identified: the natural frequency, the hub response at resonance, the fixed system damping, the damping ratio, and the modal mass. The complete transfer functions are presented, and the detailed test results are included as an appendix.

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SHAKE TEST OF ROTOR TEST APPARATUS WITH BALANCE DAMPERS IN THE 40- BY 80-FT WIND TUNNEL

Wayne Johnson* and James C. Biggers**

Ames Research Center
Moffett Field, California

SUMMARY

A shake test was conducted to determine the dynamic characteristics of a Rotor Test Apparatus on two strut systems with balance dampers in the Ames 40- by 80-ft wind tunnel. The rotor-off hub transfer function (acceleration per unit force as a function of frequency) was measured in the longitudinal and lateral directions, using a combination of broadband and discrete frequency excitation techniques. The dynamic data are summarized for the configurations tested, giving the following properties for each mode identified: the natural frequency, the hub response at resonance, the fixed system damping, the damping ratio, and the modal mass. The complete transfer functions are presented, and the detailed test results are included as an appendix.

INTRODUCTION

A shake test was conducted to establish the dynamic characteristics of a Rotor Test Apparatus (RTA) on two strut configurations with balance dampers in the Ames 40- by 80-ft wind tunnel. Of interest were potential resonances at the 1/rev and N/rev frequencies of rotors likely to be tested on the RTA, and potential ground resonance instabilities. A previous series of shake tests (reference 1) established the characteristics of the system without the balance dampers installed. The purpose of the balance dampers is to improve the ground resonance stability of the system, and to reduce the response of the balance and scales to exciting forces from the rotor.

The shake test was performed on the RTA module, without a rotor, to determine the principle frequencies and damping of the structure. The

*Research Scientist, U.S. Army Air Mobility Research and Development Laboratory

**Research Scientist, National Aeronautics and Space Administration

rotor-off hub transfer function was measured in the longitudinal and lateral directions: longitudinal, inplane acceleration of the hub due to longitudinal, inplane force; and lateral, inplane acceleration of the hub due to lateral, inplane force. With the hub transfer functions it is possible to evaluate potential ground resonance and vibration problems of rotors to be test on the RTA. This report is a continuation of reference 1, which describes in detail the test procedure and data reduction techniques.

SYSTEM AND TEST APPARATUS

The system tested consisted of the RTA module, without a rotor, on the struts and balance frame in the 40- by 80-ft wind tunnel. The RTA module included the rotor hub, with the transmission locked, and two 1500-HP electric motors installed. Two strut/tip configurations were tested: a short strut system (8-ft struts with 5-ft tips) and a long strut system (15-ft struts with 6-in tips). The short struts gave softer support of the module because of the flexibility of the tips. The tests were conducted with two balance damper installations, shown schematically in figure 1: a four damper configuration (test 458) and an eight damper configuration (test 463). The balance dampers are viscous dampers attached in the lateral or longitudinal direction between the floating frame and the balance house structure.

A hydraulic shaker was attached to the blade grip of the rotor hub to excite the module by application of an inplane force in the longitudinal or lateral direction. The other end of the shaker was attached to an 11600 lb reaction mass suspended from a crane. A load cell between the shaker and hub measured the applied force. An accelerometer on the hub measured the longitudinal or lateral response. The applied force and resulting hub acceleration data were analyzed on-line to determine the dynamic characteristics of the system, using the Dynamic Analysis System. The DAS is basically a time series analyzer and computer, utilizing Fast Fourier Transform techniques and associated software, and programs specific to this shake test.

TEST PROCEDURE AND ANALYSIS

The shake test procedures and data reduction techniques are described in detail in reference 1. There was continued refinement of the parameters

used in earlier tests. To reduce the noise level in the transfer function measurement, the total sample time was increased, the number of samples per record decreased, and the number of averages increased. The damping ratio and modal mass were calculated from integrals of the transfer function, as described in Appendix E of reference 1. The following test procedures and parameters were used:

1) Broadband excitation with .5-9 Hz bandwidth, ± 300 lb amplitude

    sample rate = 20.48/sec
    number of samples = 256
    number of records = 40
    Hanning smoothing of spectrum
    internal filter = 10 Hz low pass
    total sample time = 500 sec
    spectrum frequency increment = .08 Hz

2) Broadband excitation with .5-35 Hz bandwidth, ± 150 lb amplitude

    sample rate = 81.92/sec
    number of samples = 256
    number of records = 80
    Hanning smoothing of spectrum
    internal filter = 50 Hz low pass
    total sample time = 250 sec
    spectrum frequency increment = .32 Hz

3) Discrete excitation of balance and strut modes. At resonance frequency (identified by the broadband excitation results), force level sweep: from minimum force which gives good load cell signal, to maximum force within module acceleration limits. At maximum force of the sweep, vary frequency until locate peak of response (maximum amplitude and/or 90° phase of response).

    sample rate = 20.48/sec
    number of samples = 512
    number of records = 1
    internal filter = 10 Hz low pass
    total sample time = 25 sec
    spectrum frequency increment = .04 Hz

The following three configurations were tested, with longitudinal and lateral excitation for each:

1) Short struts with 4 balance dampers (test 458)
2) Long struts with 4 balance dampers (test 458)
3) Long struts with 8 balance dampers (test 463)

TABLE 1. Summary of Dynamic Characteristics: RTA on Short Struts.

Longitudinal Modes / Lateral Modes

Mode	ω Hz	H g/1000 lb	H in/1000 lb	C_s lb/fps	C_s* lb/fps	ζ %	M lb	Mode	ω Hz	H g/1000 lb	H in/1000 lb	C_s lb/fps	C_s* lb/fps	ζ %	M lb
****** NO DAMPERS ******															
balance	1.72	.21	.69	1400	650	3.5	60000	balance	2.15	1.15	2.43	350	350	1.9	22000
strut	3.04	.38	.40	1200	800	2.2	46000	strut	3.52	.41	.32	1500	1500	2.9	38000
bal. vert.	7.32	.15	.03	4700		1.2	140000	mast	23.2	3.2	.06	1300		6.5	2300
mod. vert.	10.0	.90	.09	1900		2.6	19000	mast	27.7	2.6	.03	1500		5.1	2700
XB vert.	14.1	.70	.03	3600		4.4	15000								
mast	25.5	3.2	.05	1400		7.0	2000								
****** BALANCE LOCKED ******															
strut	2.27	.78	1.47	440		1.0	48000	strut	2.45	1.40	2.23	300		1.0	30000
mod. vert.	10.0	.80	.08	2300		3.1	19000	mast	23.2	2.0	.04	2300		11.0	2300
XB vert.	15.3	.50	.02	5500		6.1	15000	mast	27.7	1.9	.02	2800		9.6	2700
mast	25.5	2.5	.04	2000		10.0	2000								
****** 4 BALANCE DAMPERS ******															
Balance	1.76	.10	.32	4000	2600	9.7	60000	balance	2.16	.80	1.68	470	470	2.6	22000
strut	3.04	.16	.17	3000	2600	5.5	46000	strut	3.68	.14	.10	2700	2500	5.0	38000
bal. vert.	7.36	.14	.03	4700		1.2	140000	mast	23.2	3.2	.06	1300		6.5	2300
mod. vert.	10.0	.90	.09	1900		2.6	19000	mast	27.7	2.6	.03	1500		5.1	2700
XB vert.	14.1	.71	.03	3600		4.4	15000								
mast	25.5	3.2	.05	1400		7.0	2000								

*Large Amplitude Motion

TABLE 2. Summary of Dynamic Characteristics: RTA on Long Struts.

Longitudinal Modes								Lateral Modes							
Mode	ω Hz	H g/1000 lb	H in/1000 lb	C_s lb/fps	C_s* lb/fps	ζ %	M lb	Mode	ω Hz	H g/1000 lb	H in/1000 lb	C_s lb/fps	C_s* lb/fps	ζ %	M lb
					******		NO DAMPERS		*******						
balance	1.62	.09	.34	3600	1300	7.6	75000	bal. side	2.32	.21	.38	1800	1000	2.7	75000
strut	4.02	.85	.51	700	500	1.9	33000	bal. yaw	2.67	.18	.25	2800	2000	5.0	54000
bal. vert.	7.20	.09	.02	6500		3.3	70000	strut	4.50	1.24	.60	600		0.9	39000
mod. vert.	10.6	.70	.06	1900		2.4	19000	mast	23.2	1.9	.03	1800		8.6	2300
XB vert.	14.1	.65	.03	3600		4.4	15000	mast	27.7	2.5	.03	1500		5.1	2700
mast	25.5	2.5	.04	1400		7.0	2000								
					******		BALANCE LOCKED		******						
strut	3.07	1.20	1.24	500		1.0	42000	strut	3.47	1.55	1.26	400		1.0	30000
mod. vert.	10.2	.85	.08	2100		2.8	19000	mast	23.2	1.5	.03	2300		11.0	2300
XB vert.	15.2	.60	.03	4800		5.4	15000	mast	27.7	2.2	.03	1700		5.8	2700
mast	25.5	2.1	.03	1700		8.5	2000								
					******		4 BALANCE DAMPERS		******						
balance	2.03	.08	.19	4500	4000	7.6	75000	balance	2.60	.19	.27	2900	2000	7.0	41000
strut	4.20	.49	.27	1700	1200	3.1	33000	strut	4.63	.64	.29	1400	1000	2.7	29000
bal. vert.	7.28	.12	.02	6500		3.3	70000	mast	23.2	1.9	.03	1800		8.6	2300
mod. vert.	10.0	.95	.09	1900		2.6	19000	mast	27.7	2.5	.03	1500		5.1	2700
XB vert.	14.2	.80	.04	3600		4.3	15000								
mast	25.5	2.5	.04	1400		7.0	2000								
					******		8 BALANCE DAMPERS		******						
Balance	2.17	.07	.15	5400	5100	7.8	83000	bal. side	1.74	.08	.25	3300	3000	4.0	130000
strut	4.23	.37	.20	2600	2000	4.6	34000	yaw	2.68	.23	.32	2400	2000	6.4	35000
bal. vert.	7.32	.12	.02	6500		3.3	70000	strut	4.04	.15	.09	4100	4000	5.7	52000
mod. vert.	9.9	.84	.08	1900		2.6	19000	mast	22.7	2.9	.05	1500		5.7	3000
XB vert.	14.1	.80	.04	3600		5.5	12000	mast	27.7	3.0	.04	1700		6.3	2500
mast	22.7	2.3	.04	1600		7.0	2600								

*Large Amplitude Motion

RESULTS

The results of this test are the dynamic characteristics of the configurations investigated, specifically, the frequencies and response amplitudes of the principal modes identifiable in the hub transfer functions. Figures 2 through 4 present the transfer functions for the three configurations tested. The lateral and longitudinal hub responses are shown, in the 9 and 35 Hz excitation ranges for each. The abscissas in the figures are frequency, from 0 to 10 or 50 Hz, and the ordinates are the magnitude of the transfer function in g/1000 lb. Figures 5 and 6 present the longitudinal and lateral transfer functions for the short struts with four balance dampers, obtained during discrete frequency sweeps using analog data reduction techniques (c.f. broadband excitation results, figure 2).

Tables 1 and 2 summarize the dynamic characteristics of the RTA on the short and long struts, including the results of reference 1. The tables give the following quantities for each of the longitudinal and lateral modes identified in the hub response: the resonant frequency ω (Hz); the magnitude of the hub response H (g/1000 lb and in/1000 lb); the fixed system damping coefficient C_s (lb/fps) and the damping for large amplitude motion; the damping ratio (per-cent critical damping); and the modal mass M (lb).

The test data show a nonlinear behavior for the damping of the low frequency modes. The damping for high excitation level and high response amplitude is generally lower than the damping measured at low levels. Figures 7 through 9 show the damping of the low frequency modes as a function of force level for the three configurations tested. Tables 1 and 2 also present the fixed system damping level for large amplitude motion.

The tables of Appendix A present in detail the shake test data for the three configurations investigated, and also for a number of special runs.

REFERENCES

1. Johnson, Wayne, and Biggers, James C., "Shake Test of Rotor Test Apparatus in the 40- by 80-ft Wind Tunnel," NASA TM X-62,418, February 1975

APPENDIX A

Rotor Test Apparatus Shake Test Data

The tables of this appendix present the data for the resonant frequencies of the hub transfer functions (lateral acceleration due to lateral force, and longitudinal acceleration due to longitudinal force). The following configurations were tested:

Table A1. Short struts with 4 balance dampers (test 458)
Table A2. Long struts with 4 balance dampers (test 458)
Table A3. Long struts with 8 balance dampers (test 463)
Table A4. Special configurations.

The following quantities are given in the tables: the resonant frequency ω (Hz); the amplitude of the hub response H (g/1000 lb and in/1000 lb); the phase of the response $\angle H$ (degrees); the fixed system damping of the mode C_s (lb/fps); the damping ratio ζ (per-cent critical damping); the modal mass M (lb); and the amplitude of the exciting force F at that frequency (lb, with "D" indicating discrete frequency excitation). Several sweeps of discrete frequency excitation in the vicinity of resonances were made, and the data are given for the entire sweep as well as for the peak.

Table A1. Short struts with 4 balance dampers (test 458).

Run/Pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % crilical	M lb	F lb D = discrete
	longitudinal modes							
5/1	1.76	.096	.302	-89	4061	9.8	60700	3.7
2	1.76	.096	.303	-93	3700	9.2	58970	8.0
7/1	1.78	.11	.34	-87	3200	10.4	44000	D70
5/10	1.76	.069	.218	-93	4970			D16
11	1.76	.092	.289	-92	3750			D42
12	1.76	.097	.307	-92	3540			D67
13	1.76	.122	.386	-101	2760			D108
14	1.76	.131	.414	-106	2520			D135
15	1.76	.132	.417	-108	2460			D160
30	1.84	.174	.502	-88	2070			D171
5/1	3.03	.161	.170	-56	3063	6.2	53700	6
2	3.06	.152	.161	-56	3234	5.7	58100	11.7
7/1	3.05	.195	.19	-50	2450	5.5	49000	D70
5/18	3.04	.157	.166	-47	2770			D18
19	3.04	.171	.181	-47	2573			D52
20	3.04	.172	.182	-49	2626			D86
21	3.04	.172	.182	-49	2600			D121
22	3.04	.171	.181	-59	2970	5.2	51000	D171

Table A1. (continued)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	longitudinal modes							
5/25	2.88	.123	.145	−100	4488			D171
24	2.92	.144	.165	−92	3970			D160
26	3.00	.167	.181	−73	3353			D 165
22	3.04	.171	.181	−59	2970			D 171
23	3.08	.163	.168	−47	2704			D 188
5/27	1.76	.153	.482	−119	1976			D 216
28	1.80	.171	.515	−106	1982			D 206
30	1.84	.174	.502	−88	2068			D 202
29	1.88	.157	.435	−74	2241			D 217

Table A1. (continued)

Run/ pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	lateral modes							
2/4	2.18	.414	.836	152	484	2.4	23600	2.8
6	2.16	.60	1.26	92	600	2.9	24600	1.1
4/1	2.12	.75	1.63	90	552	3.8	17600	D100
1/4	2.12	.738	1.604	105	583	3.0	23500	2.8
1/11	2.12	.861	1.871	95	479			D19
12	2.12	.802	1.745	113	474			D27
13	2.12	.882	1.919	92	469			D13
14	2.12	.775	1.685	120	461			D34
15	2.12	.861	1.873	102	471			D48
2/1	2.12	.835	1.81	112	460			D38
2	2.12	.833	1.81	112	460			D38
3	2.12	.835	1.82	113	457			D37
10	2.12	.780	1.70	109	502			D25
11	2.12	.792	1.72	114	477			D40
12	2.12	.87	1.89	90	476			D52
14	2.12	.729	1.59	121	485			D30
31	2.18	.913	1.91	93	462			D59
30	2.16	.887	1.86	82	471	2.7	20900	D38

Table A1. (continued)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$ H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	lateral modes							
2/4	3.6	.15	.11	144	2760	5.0	39200	
6	3.68	.139	.100	148	2911	6.9	40000	78
1/4	3.65	.154	.113	151	2950	5.9	35000	17
4/1	3.68	.121	.09	135	2970			D100
2/17	3.68	.132	.095	140	3535			D41
18	3.68	.139	.100	154	2250			D89
19	3.68	.137	.099	157	2089			D111
21	3.60	.140	.105	151	2448	5.5	31800	D150
2/29	2.08	.621	1.40	49	492			D92
26	2.12	.745	1.62	61	488			D91
13	2.12	.724	1.37	61	500			D92
30	2.16	.887	1.86	82	471			D88
32	2.18	.837	1.75	69	472			D91
27	2.20	.718	1.45	126	487			D94
28	2.24	.353	.69	156	5301			D93
2/20	3.68	.133	.096	158	2003			D140
21	3.60	.140	.105	151	2448			D150
22	3.52	.137	.109	137	3410			D137
23	3.44	.112	.092	124	4984			D149
24	3.36	.085	.074	122	6506			D164
25	3.28	.072	.072	129	6899			D152

Table A1. (concluded)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	F lb		Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	F lb
	longitudinal modes						lateral modes			
5/1	7.36	.142	.026	4.7		2/5	22.4	3.34	.065	1.9
2	7.36	.125	.023	8.1		4/1	22.5	4.0	.08	Δ100
7/1	7.4	.19	.03	Δ70		1/5	23.0	3.13	.057	1.8
						6	22.4	3.14	.061	6.3
5/3	10.0	.88	.087	4.0						
4	10.0	.97	.097	7.8		2/5	26.9	2.58	.035	3.2
7/1	10.0	2.0	.20	Δ70		4/1	26.3	2.7	.04	Δ100
						1/5	27.2	2.6	.03	
5/3	14.1	.71	.035	5.2		6	26.9	2.66	.036	6.0
4	14.1	.72	.036	10.0						
7/1	14.1	.92	.05	Δ70						
5/3	24.5	3.16	.051	3.1						
4	24.3	3.12	.052	5.4						
7/1	24	2.8	.05	Δ70						
5/3	28.5	1.35	.016	3.6						
7/1	28.5	1.3	.015	Δ70						
5/3	31.2	1.40	.014	2.4						
7/1	31.2	1.2	.012	Δ70						
5/3	35.0	1.49	.012	2.1						
7/1	35.0	1.4	.011	Δ70						

Table A2. Long struts with 4 balance dampers (test 458)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	∠H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	longitudinal modes							
17/7	2.03	.088	.21	−117	4388	7.4	75560	12
10	2.03	.08						
26	2.04	.087	.20	−94	4479	7.5	74860	14
46	2.04	.083	.19	−97	4602	7.9	73810	16
13	2.03	.087	.22	−121	4600	7.4	76800	19
8	2.02	.102	.25	−119	3350			D123
15	2.02	.089	.22	−113	4020			D53
16	2.02	.093	.22	−116	3938			D91
17	2.02	.096	.23	−121	3545			D139
35	2.16	.108	.23	−88	3903			D346
17/7	4.20	.495	.269	−65	1659	3.1	32820	6
10	4.21	.487	.265	−63	1700	3.1	33540	8
26	4.20	.489	.266	−62	1673	3.0	33030	
46	4.21	.497	.270	−66	1740	3.3	32490	9
22	4.20	.726	.402	−91	1130			D34
43	4.20	.66	.37	−90	1238			D76
23	4.20	.70	.39	−83	1161	2.1	35000	D66

Table A2. (continued)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	∠ H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	longitudinal modes							
17/2	1.66	.039	.136	−163	2400			D 238
28	1.80	.054	.162	−157	2566			D 347
29	1.98	.067	.184	−151	2677			D 339
30	2.00	.093	.227	−132	3101			D 330
9	2.02	.100	.233	−125	3266			D 218
18	2.02	.095	.233	−128	3221			D 271
19	2.04	.103	.242	−123	3235			D 418
20	2.08	.107	.243	−107	3622			D 326
21	2.12	.102	.223	−92	4042			D 275
31	2.12	.108	.236	−101	3754			D 292
35	2.16	.108	.226	−88	3903			D 346
32	2.20	.092	.186	−78	4562			D 321
33	2.28	.068	.127	−63	5869			D 340
34	2.40	.040	.067	−59	10060			D 328

Table A2. (continued)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	longitudinal modes							
17/36	4.00	.268	.16	−150	1477			D 75
37	4.08	.432	.25	−136	1274			D 82
38	4.16	.62	.35	−109	1231			D 81
24	4.16	.66	.37	−109	1169			D 45
25	4.18	.70	.39	−97	1160			D 37
42	4.18	.64	.36	−101	1250			D 49
23	4.20	.70	.39	−83	1161			D 66
43	4.20	.66	.37	−90	1235			D 76
39	4.24	.63	.34	−64	1183			D 89
44	4.28	.50	.27	−46	1208			D 102
45	4.28	.51	.27	−47	1198			D 97
40	4.32	.41	.21	−33	1148			D 82
41	4.40	.28	.14	−24	1251			

Table A2. (continued)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	lateral modes							
19/1	2.59	.183	.272	76	2981	7.1	40390	9
4	2.60	.189	.292	72	2860	6.9	40840	7
17	2.60	.186	.269	86	2723			D92
18	2.60	.211	.305	76	2340			D133
20	2.68	.254	.345	90	2064			D195
19/1	4.62	.645	.293	121	1357	2.7	28480	6
4	4.64	.631	.284	111	1445	2.6	30440	4
31	4.60	.79	.37	92	1130			D31
7	4.64	.71	.32	130	981			D68
12	4.56	.76	.36	100	1160	2.5	28000	D93
19/15	4.36	.29	.15	37	1758			D 101
14	4.44	.46	.23	49	1442			D 92
13	4.52	.69	.33	76	1240			D 85
12	4.56	.76	.36	100	1160			D 93
11	4.64	.65	.30	135	990			D 109
8	4.69	.63	.28	136	999			D 120
10	4.72	.49	.22	153	861			D 124
9	4.80	.41	.17	158	948			D 95

Table A2. (continued)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	$<$ H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	lateral modes							
19/27	4.44	.27	.14	39	2009			Δ 28
28	4.52	.40	.19	47	1633			Δ 25
36	4.54	.58	.27	62	1340			Δ 21
29	4.56	.66	.31	68	1255			Δ 29
37	4.56	.62	.29	66	1309			Δ 31
31	4.60	.79	.37	92	1130			Δ 31
30	4.64	.80	.36	115	1022			Δ 34
32	4.64	.78	.36	114	1055			Δ 35
6	4.64	.75	.34	118	1062			Δ 43
35	4.68	.71	.32	133	937			Δ 46
33	4.72	.64	.28	140	927			Δ 41
34	4.80	.49	.21	153	876			Δ 44
19/26	2.36	.128	.225	29	1724			Δ 183
25	2.44	.162	.266	38	1826			Δ 179
24	2.52	.202	.311	49	1852			Δ 186
19	2.60	.252	.364	64	1819			Δ 198
20	2.68	.254	.345	90	2064			Δ 195
21	2.76	.203	.26	110	2495			Δ 213
22	2.84	.147	.179	123	3175			Δ 212
23	2.92	.108	.124	131	3973			Δ 199

Table A2. (concluded)

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	F lb		Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	F lb
	longitudinal modes						lateral modes			
17/7	7.27	.129	.024	10		19/2	23.0	1.91	.035	5
10	7.28	.118	.022	15		5	23.0	2.92	.054	2
46	7.29	.133	.025	13						
						19/2	28.2	2.56	.032	5
17/11	10.0	.92	.092	3		5	28.2	4.41	.054	2
27	10.1	.98	.091	4						
17/11	14.2	.80	.040	3						
27	14.2	.80	.039	4						
17/11	24.3	2.48	.041	3						
27	22.7	2.35	.044	3						
17/11	28.2	1.53	.019	3						
27	29.2	1.41	.017	4						
17/11	31.3	1.53	.015	2						
27	31.3	1.40	.014	3						

Table A3. Long struts with 8 balance dampers (test 463).

Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	longitudinal modes							
2/1	2.17	.0723	.152	−121	5394	7.7	83600	14
2	2.17	.0705	.148	−117	5451	7.9	82000	17
4	2.17	.0706	.148	−127	4800			D 74
5	2.17	.0731	.153	−115	5223			D 156
7	2.20	.0796	.161	−108	5152			D 289
2/1	4.23	.359	.195	−86	2670	4.7	34400	9
2	4.22	.374	.203	−80	2588	4.6	34000	11
11	4.22	.419	228	−85	1970			D 49
12	4.23	.390	.212	−72	2023			D 153
2/10	2.08	.0741	.167	−127	4361			D 252
9	2.12	.0773	.168	−121	4620			D 269
6	2.17	.0791	.166	−113	4911			D 258
7	2.20	.0796	.161	−108	5152			D 289
8	2.24	.0753	.147	−100	5728			D 276
2/15	4.12	.344	.198	−114	2140			D 174
14	4.16	.379	.214	−100	2110			D 158
12	4.23	.390	.212	−72	2023			D 153
13	4.28	.346	.185	−57	2020			D 172

Table A3. (continued)

Run/Pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	lateral modes							
1/1	1.74	.0993	.282	−123	3280	4.0	122000	11
2	1.74	.0780	.246	−130	3460	3.9	133200	18
13	1.74	.0871	.275	−138	2640			D 49
14	1.74	.0737	.243	−149	2360			D 94
15	1.80	.0749	.216	−120	~3000			D 122
1/1	2.70	.239	.316	−75	2240	6.3	34200	7
2	2.66	.227	.318	−100	2374	6.5	35200	11
5	2.68	.269	.366	−89	1948			D 69
6	2.68	.269	.367	−89	1943			D 154
26	2.68	.262	.356	−87	1996			D 150
7	2.68	.272	.370	−89	1924			D 182
1/1	4.04	.142	.094	−44	3876	5.2	55600	15
2	4.03	.154	.094	−58	4309	6.1	49500	19
18	4.04	.143	.086	−59	4720			D 62
19	4.04	.168	.100	−51	3670			D 106
22	3.92	.165	.105	−72	4420			D 143

Table A3 (continued)

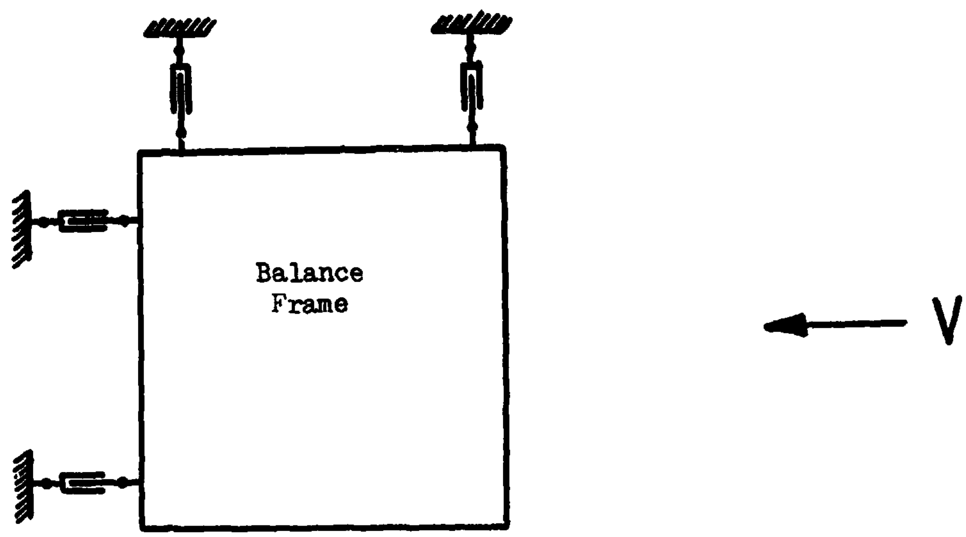
Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
	lateral modes							
1/10	2.56	.236	.352	−122	1807			Δ 176
9	2.64	.272	.382	−102	1855			Δ 182
7	2.68	.272	.370	−89	1924			Δ 192
8	2.72	.267	.353	−79	1956			Δ 204
11	2.80	.213	.266	−60	2217			Δ 214
1/16	1.74	.0693	.229	−152	2300			Δ 119
15	1.82	.0749	.216	−120	4150			Δ 122
25	1.88	.0351	.097	−84	10410			Δ 143
1/23	3.80	.136	.092	−80	5380			Δ 139
22	3.92	.165	.105	−72	4420			Δ 143
20	4.04	.172	.103	−52	3633			Δ 136
21	4.20	.147	.081	−38	3415			Δ 165

Table A3. (concluded)

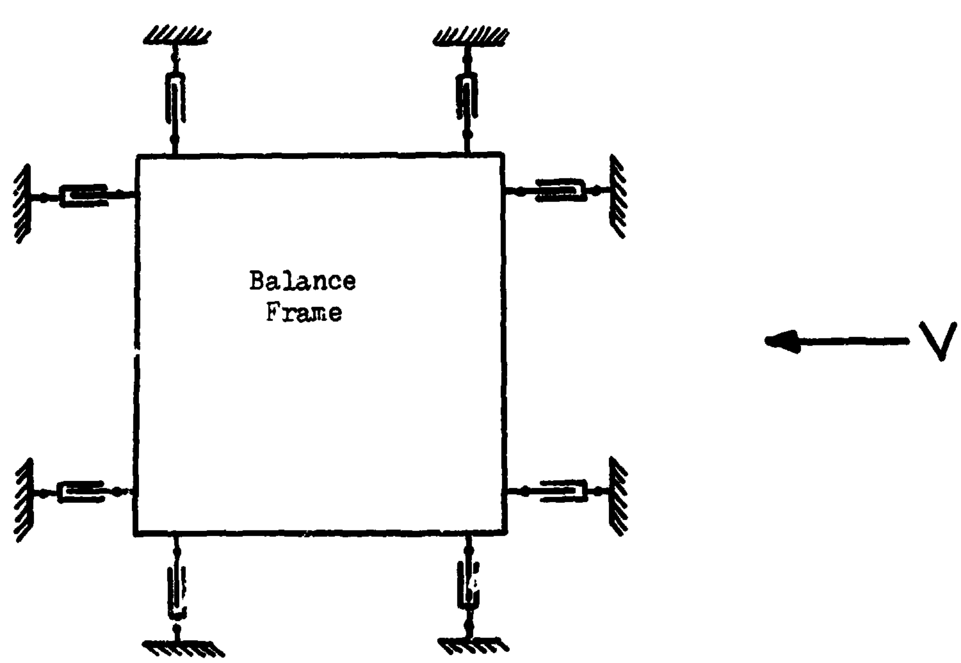
Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	F lb		Run/ Pt	ω Hz	H g/1000 lb	H in/1000 lb	F lb
	longitudinal modes						lateral modes			
2/1	7.31	.125	.023	13		1/3	22.7	2.86	.054	4
2	7.33	.131	.024	16						
2/3	9.92	.836	.083	5		1/3	27.8	3.03	.038	4
2/3	14.1	.791	.039	6						
2/3	22.7	2.34	.044	4						

Table A4. Special Configurations

Test/run/pt	ω Hz	H g/1000 lb	H in/1000 lb	$\angle$H deg	C_s lb/fps	ζ % critical	M lb	F lb D = discrete
Compensators off		long struts with 4 balance dampers, longitudinal modes						
458/18/1	2.04	.083	.204	−118	4506	7.3	78400	13
2	2.12	.101	.219	−100	4047			D309
1	4.20	.484	.263	−65	1711	3.1	33400	7
Drag scale	dash pot off	long struts with 4 balance dampers, longitudinal modes						
458/18/3	2.04	.084	.205	−118	4465	7.2	78500	15
4	2.12	.105	.227	−101	3387			D339
3	4.20	.481	.262	−64	1726	3.2	33600	9
Hydraulic snubbers engaged		long struts with 4 balance dampers, longitudinal modes						
458/18/5	3.15	.727	.730	−145	502	1.0	41660	3
5	7.79	.22	.036	−152	3220			9
Hydraulic snubbers engaged		long struts with 4 balance dampers, lateral modes						
458/19/3	3.48	.963	.760	153	390	1.0	27790	4

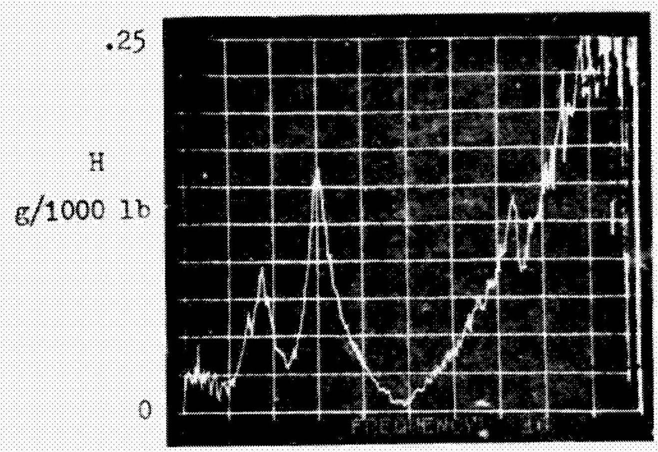


a) 4 damper installation (test 458)

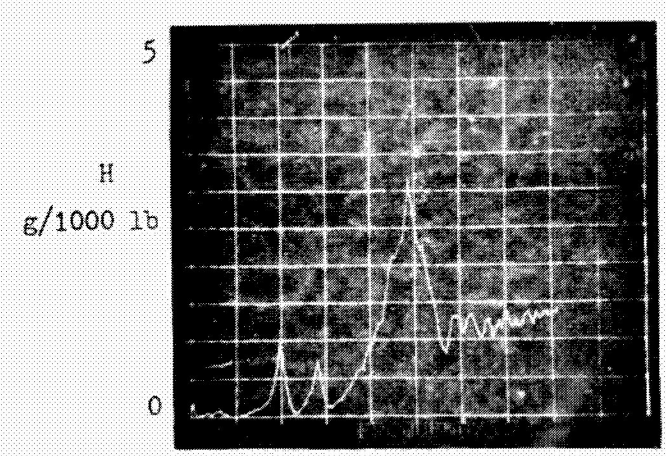


b) 8 damper installation (test 463)

Figure 1. Schematic of balance-frame viscous damper installations for tests 458 and 463 (top view).



.5-9 Hz broadband excitation, longitudinal hub response
(test 458, run 5, point 1)



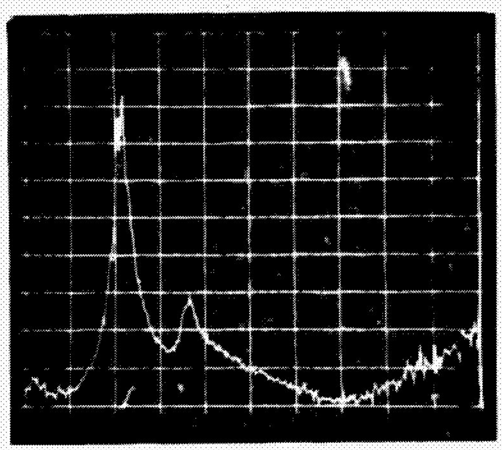
.5-35 Hz broadband excitation, longitudinal hub response
(test 458, run 5, point 4)

Figure 2. Short struts with 4 balance dampers.

.5

H
g/1000 lb

0

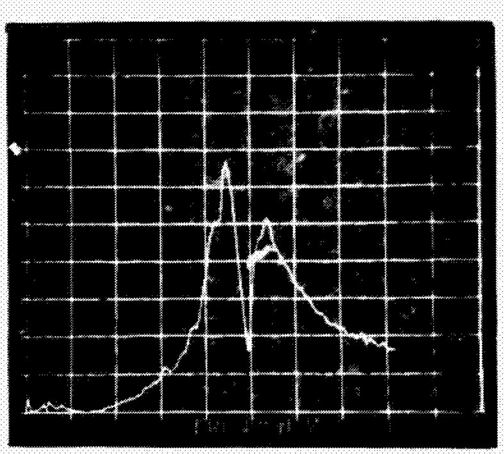


.5-9 Hz broadband
excitation, lateral
hub response
(test 458, run 2, point 4)

5

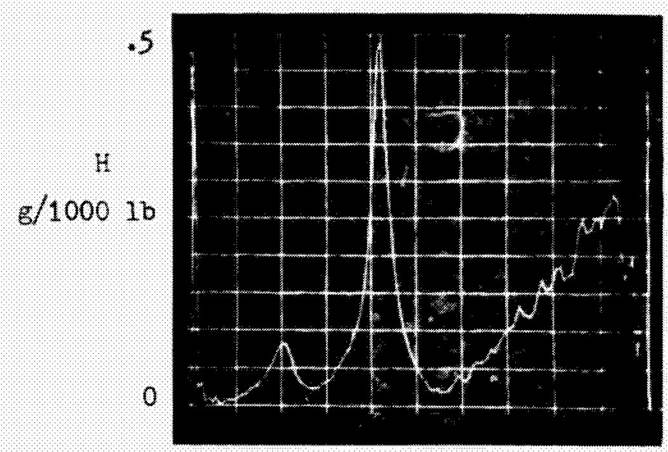
H
g/1000 lb

0

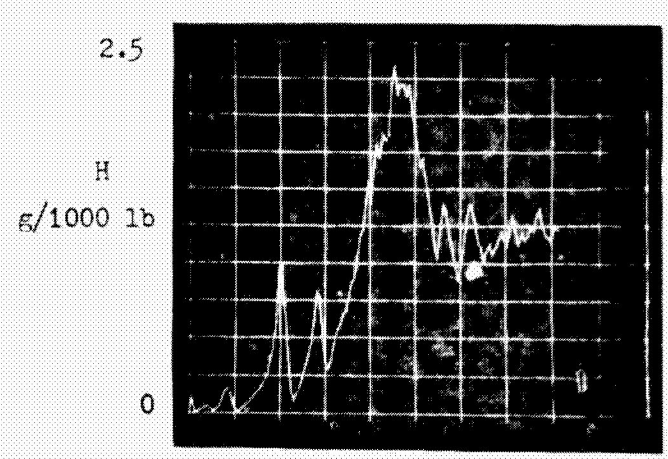


.5-35 Hz broadband
excitation, lateral
hub response
(test 458, run 2, point 5)

Figure 2. (concluded)



.5-9 Hz broadband excitation, longitudinal hub response
(test 458, run 17, point 46)



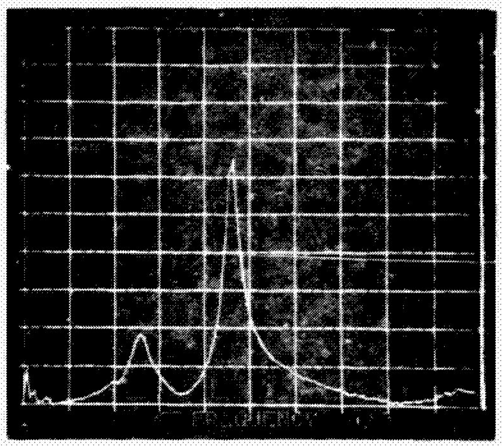
.5-35 Hz broadband excitation, longitudinal hub response
(test 458, run 17, point 27)

Figure 3. Long struts with 4 balance dampers.

1

H
g/1000 lb

0

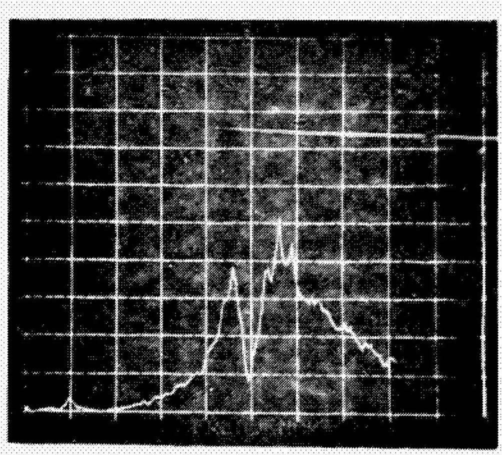


.5-9 Hz broadband
excitation, lateral
hub response
(test 458, run 19, point 1)

5

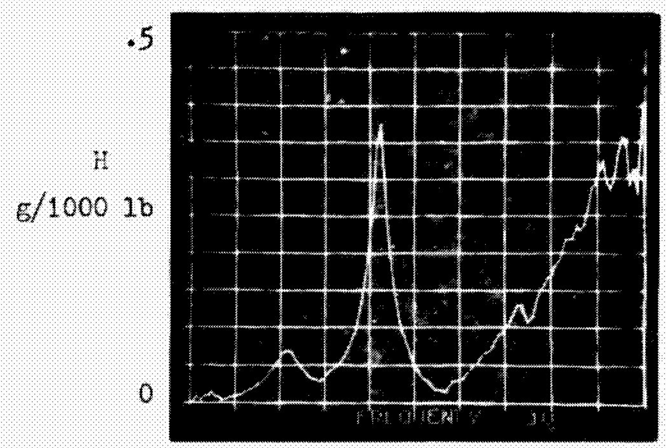
H
g/1000 lb

0

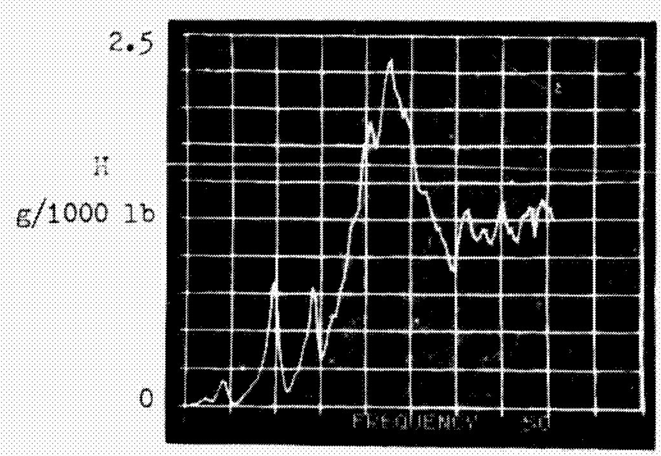


.5-35 Hz broadband
excitation, lateral
hub response
(test 458, run 19, point 2)

Figure 3. (concluded)



.5-9 Hz broadband
excitation, longitudinal
hub response
(test 463, run 2, point 2)



.5-35 Hz broadband
excitation, longitudinal
hub response
(test 463, run 2, point 3)

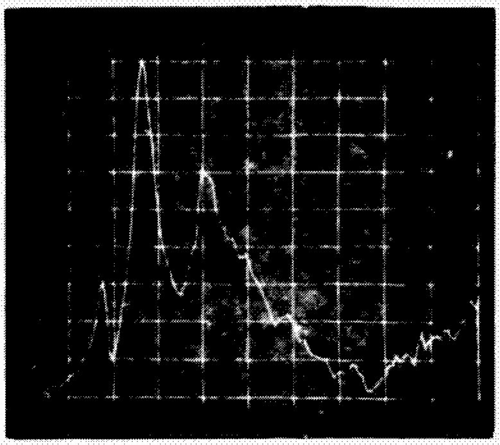
Figure 4. Long struts with 8 balance dampers

.25

H

g/1000 lb

0



.5-9 Hz broadband excitation, lateral hub response

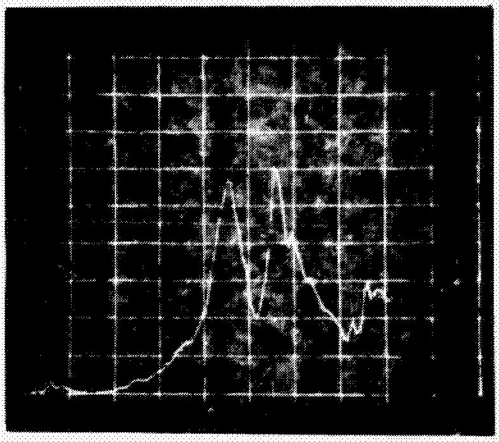
(test 463, run 1, point 2)

5

H

g/1000 lb

0



.5-35 Hz broadband excitation, lateral hub response

(test 463, run 1, point 3)

Figure 4. (concluded)

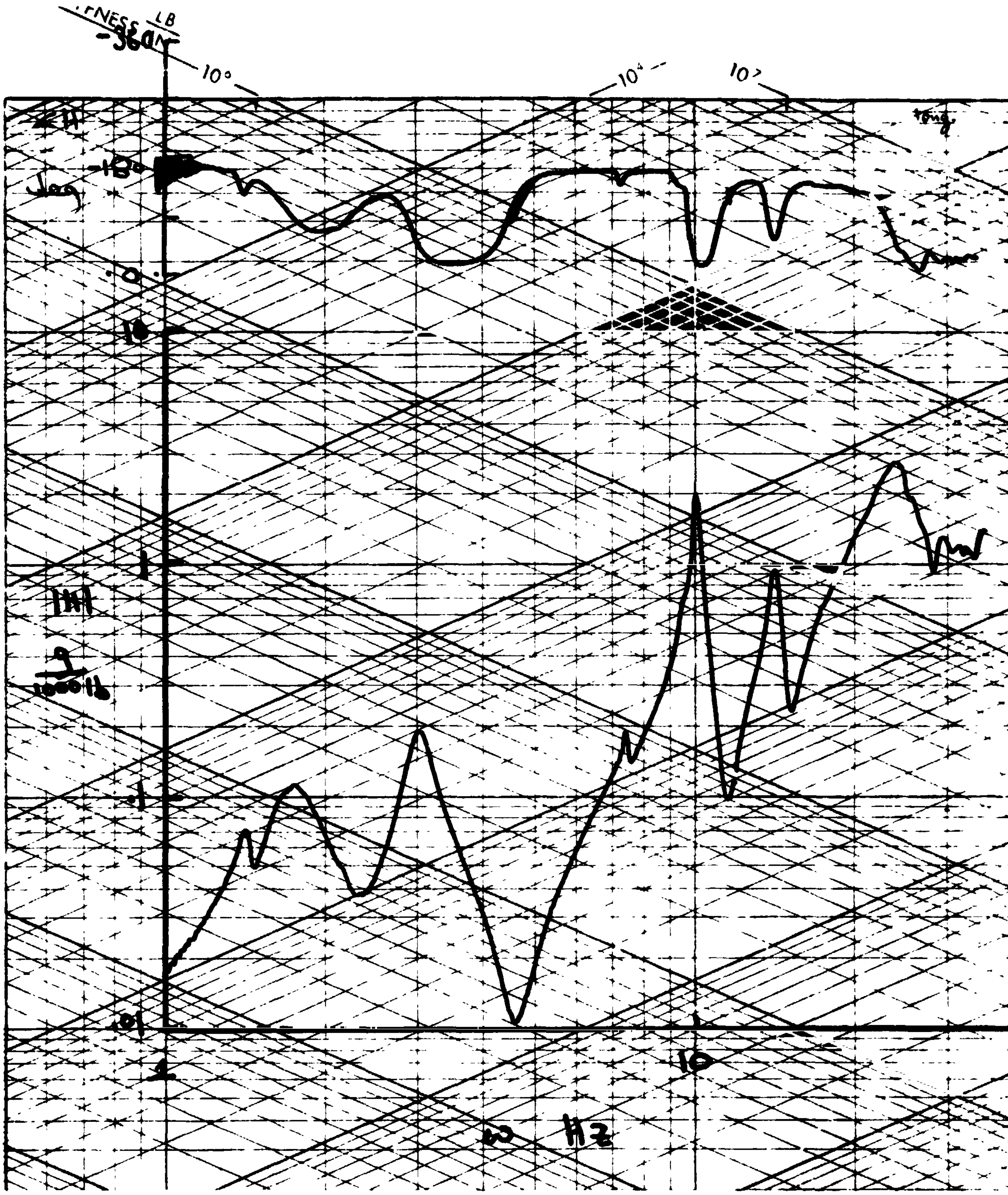


Figure 5. Transfer function of longitudinal hub response, for RTA on short struts with 4 balance dampers. Discrete frequency sweep at 70 lb excitation level (run 7, point 1, test 458).

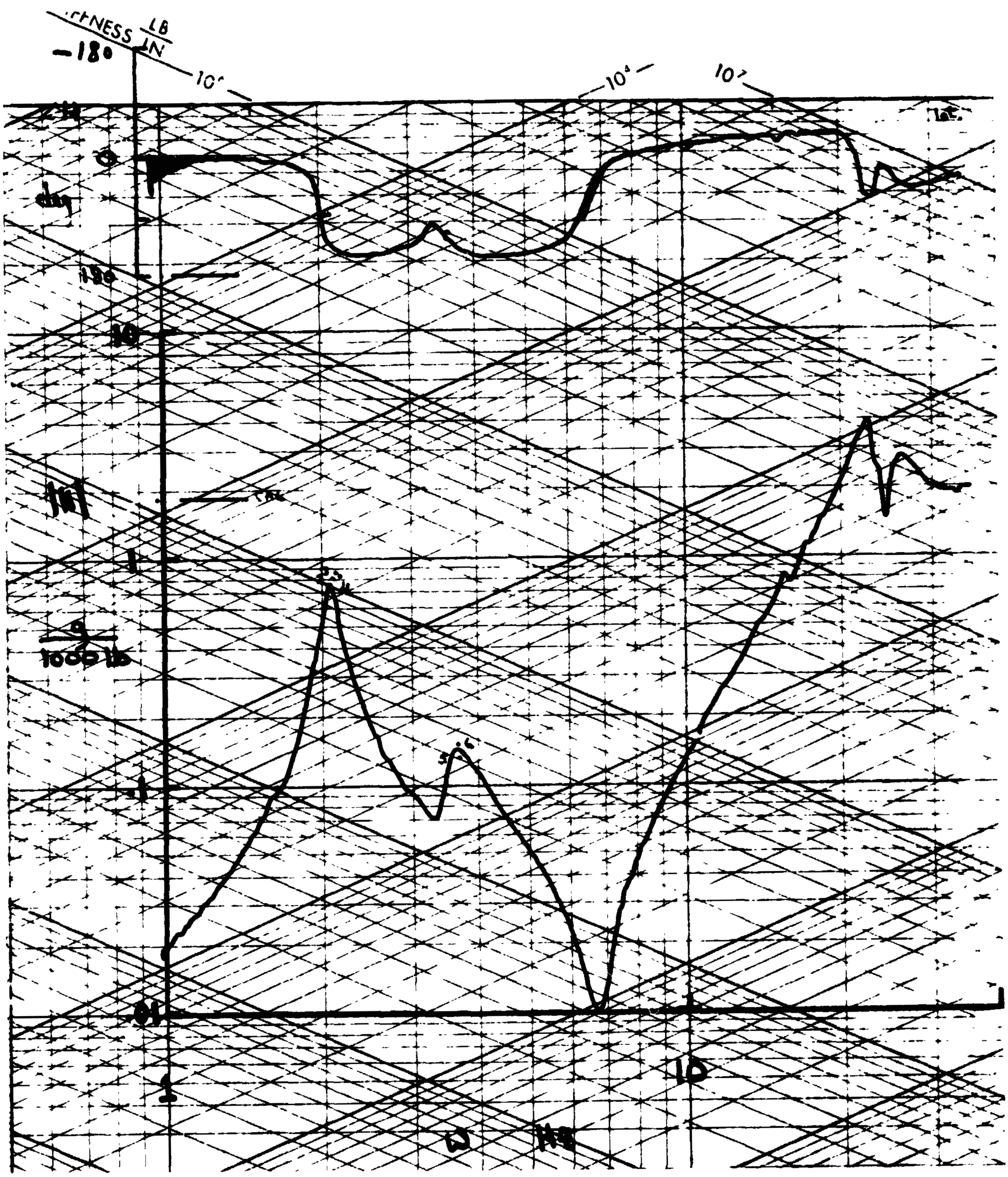


Figure 6. Transfer function of lateral hub response, for RTA on short struts with 4 balance dampers. Discrete frequency sweep at 100 lb excitation level (run 4, point 1, test 458).

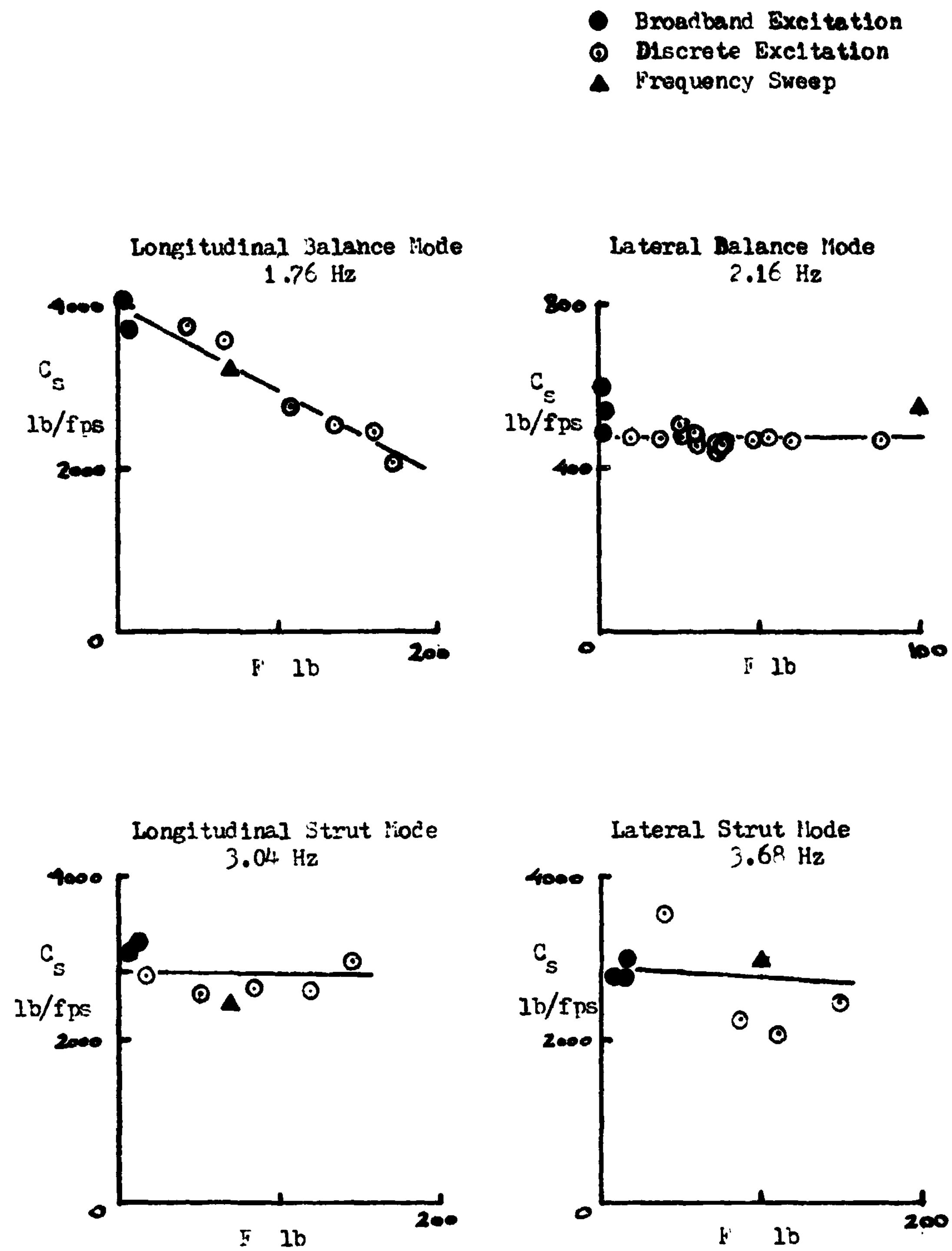


Figure 7. Variation of modal damping with excitation level: MTA on short struts with 4 dampers (test 458).

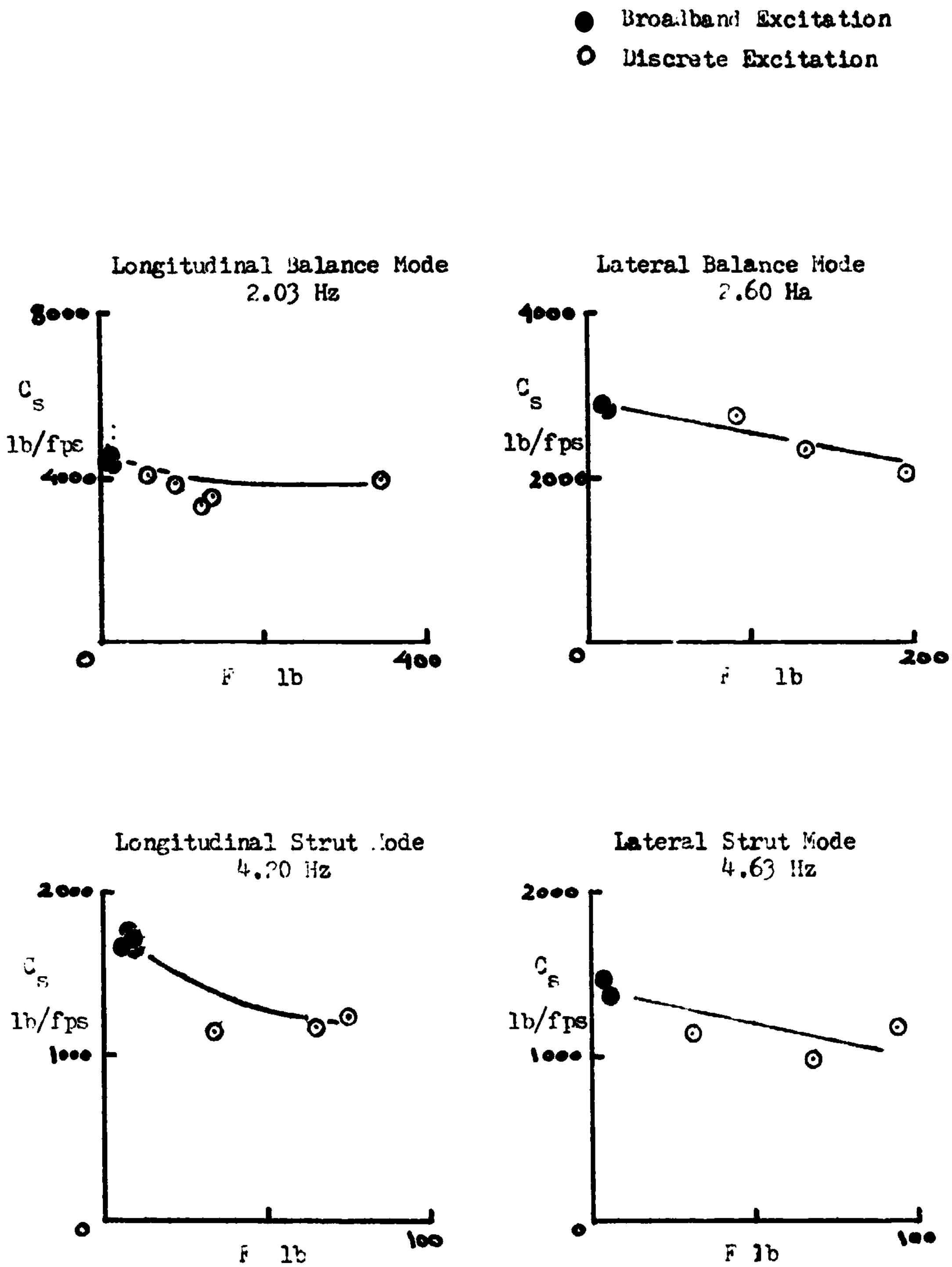


Figure 8. Variation of modal damping with excitation level: RTA on long struts with 4 balance dampers (test 458)

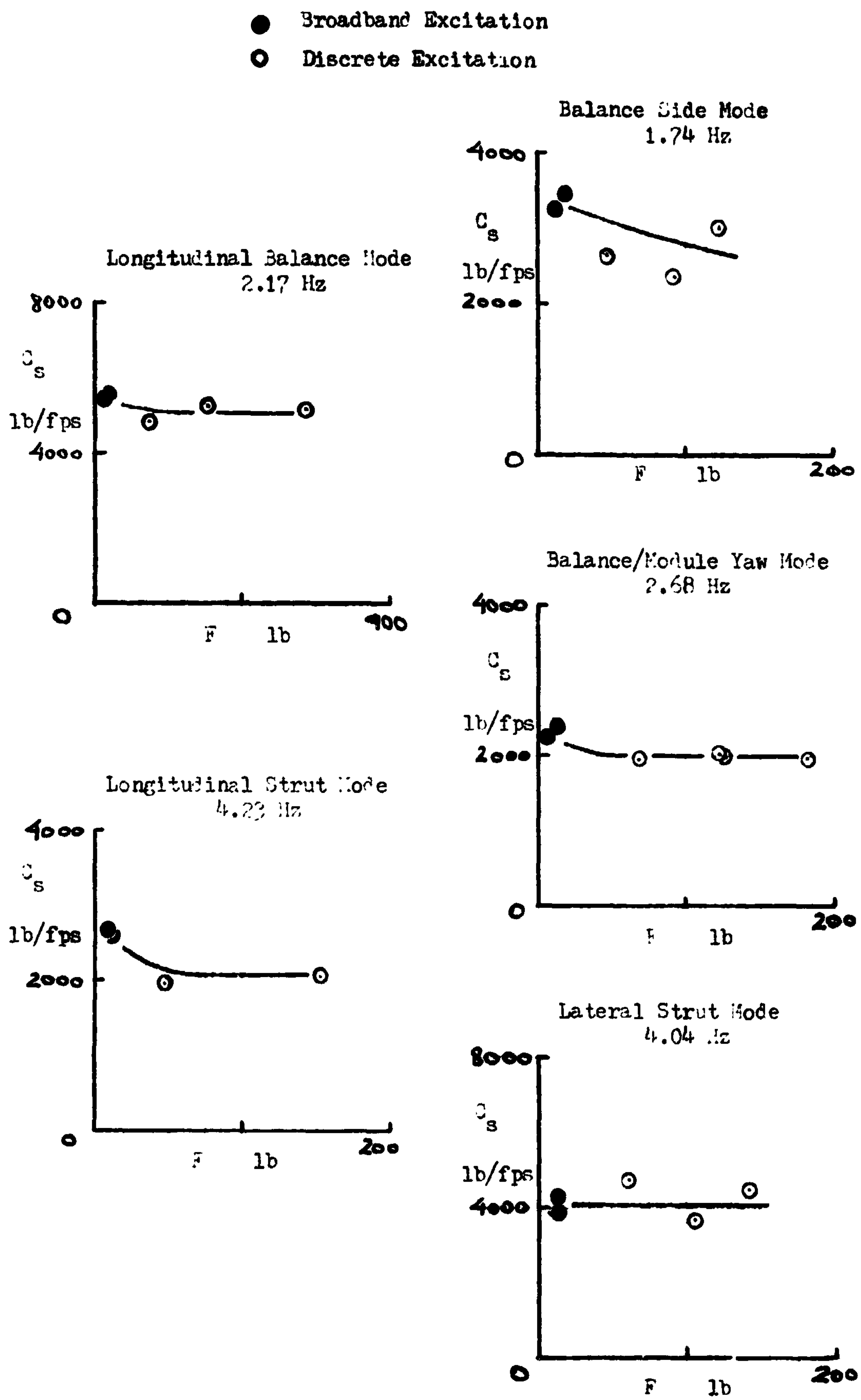


Figure 9. Variation of modal damping with excitation level: MTA on long struts with 8 balance dampers (test 46[illegible]).